



Archives available at [journals.mriindia.com](http://journals.mriindia.com)

**International Journal of Recent Advances in Engineering and Technology**

ISSN: 2347 - 2812

Volume 15 Issue 01, 2026

## AI-Based Research and Experimental Analytical Assessment of Environmental and Economic Impacts of Fly Ash Utilization in Building Projects

<sup>1</sup>Ms. Isha Sharad Deore, <sup>2</sup>Dr. Pravin D. Nemade

<sup>1</sup>Research Scholar, Department of Civil (Construction & Management)

Maratha Vidya Prasarak Samaj's Karmaveer Adv. Baburao Ganpatrao Thakare College of Engineering Udoji Maratha Boarding Campus, Near Pumping Station, Gangapur Road, Nashik an Autonomous Institute Permanently affiliated to Savitribai Phule Pune University

<sup>2</sup>Ph. D. (Civil Engineering)

Professor, Head of Department Karmaveer Adv. Baburao Ganpatrao Thakare College of Engineering Nashik an Autonomous Institute

Email: <sup>1</sup>ishadeore27122001@gmail.com, <sup>2</sup>hod.civil@kbtcoe.org

### Peer Review Information

Submission: 02 Jan 2026

Revision: 23 Jan 2026

Acceptance: 15 Feb 2026

### Keywords

Geopolymer Concrete (GPC); Fly Ash Utilization; Ground Granulated Blast Furnace Slag (GGBS); AI-Based Analytical Modeling; Life Cycle Assessment (LCA); Carbon Emission Reduction; Sustainable Construction Materials; Durability Performance; Alkaline Activation; Environmental Impact Assessment; Cost-Effectiveness Analysis.

### Abstract

The construction industry significantly contributes to global carbon emissions, primarily due to the extensive use of Ordinary Portland Cement (OPC) in conventional concrete (CC). Cement manufacturing is energy-intensive and responsible for substantial CO<sub>2</sub> emissions, leading to environmental degradation and climate change. Additionally, conventional concrete exhibits durability challenges when exposed to aggressive environmental conditions such as sulfate attack, acid exposure, and high temperatures. In this context, Geopolymer Concrete (GPC), synthesized using industrial by-products such as fly ash and Ground Granulated Blast Furnace Slag (GGBS) activated by alkaline solutions, has emerged as a promising sustainable alternative. This research presents an AI-based research and experimental analytical assessment of the environmental and economic impacts of fly ash utilization in building projects by comparing GPC with conventional M-30 grade concrete. The experimental methodology involves the design and development of M-30 grade GPC using fly ash and GGBS as binder materials activated with sodium hydroxide (NaOH) and sodium silicate (Na<sub>2</sub>SiO<sub>3</sub>) solutions. Mechanical performance will be evaluated using compressive, split tensile, and flexural strength tests on cube, cylinder, and beam specimens. Durability assessment will include water absorption tests to evaluate porosity and permeability, acid and sulfate resistance tests to analyze chemical durability, and thermal resistance tests to assess performance under elevated temperatures. Furthermore, a comprehensive Life Cycle Assessment (LCA) will be conducted to quantify CO<sub>2</sub> emissions, embodied energy, and environmental impacts associated with both GPC and CC. AI-based analytical modeling techniques will be employed to predict performance trends, optimize mix proportions, and evaluate sustainability indicators. The proposed work aims to establish a comparative framework for assessing strength, durability, carbon footprint, and cost-effectiveness of GPC and CC. Expected outcomes include significant reduction in CO<sub>2</sub> emissions due

	<p>to partial or complete replacement of OPC, improved resistance to aggressive environments, enhanced thermal stability, and long-term economic benefits through reduced maintenance and lifecycle costs. AI-driven analysis is anticipated to improve predictive accuracy and decision-making for sustainable construction practices. The study concludes by proposing geopolymer concrete as a technically viable, environmentally sustainable, and economically feasible alternative to conventional concrete for structural applications, particularly in M-30 grade construction, without compromising mechanical performance and durability.</p>
--	---

### Introduction

The rapid growth of the construction industry has significantly increased the demand for Ordinary Portland Cement (OPC)-based concrete, making it one of the largest contributors to global carbon dioxide (CO<sub>2</sub>) emissions. Cement production alone accounts for nearly 7–8% of global CO<sub>2</sub> emissions, leading to severe environmental concerns such as global warming and climate change. Consequently, the development of sustainable construction materials has become a priority in civil engineering research. Recent studies emphasize the urgent need to replace OPC with alternative binders derived from industrial by-products to minimize environmental impact while maintaining structural performance [Wei Liang et al., 2023; Lin Chen et al., 2024].

Fly ash (FA), a by-product of coal-fired power plants, has emerged as a promising supplementary cementitious material due to its pozzolanic properties, availability, and cost-effectiveness. Several researchers have demonstrated that incorporating fly ash in concrete improves workability, durability, and long-term strength while significantly reducing embodied carbon emissions [Neha Sharma et al., 2022; Mahdi Rafieizonooz et al., 2022]. Furthermore, sustainable material reviews indicate that waste-derived construction materials can effectively reduce non-renewable energy consumption and promote circular economy principles in the building sector [Lin Chen et al., 2024; Darmansyah et al., 2023]. Geopolymer Concrete (GPC), produced through the alkaline activation of aluminosilicate materials such as fly ash and Ground Granulated Blast Furnace Slag (GGBS), has gained attention as an eco-friendly alternative to conventional concrete. Unlike OPC-based systems, geopolymer binders significantly reduce CO<sub>2</sub> emissions and energy consumption during production. Research findings reveal that optimized fly ash-slag combinations can enhance compressive, tensile, and flexural strengths while improving resistance to chloride penetration and sulfate

attack [Muhammad Hassan Ashfaq et al., 2024; Vinay Mohan Agrawal et al., 2023]. Additionally, multi-objective optimization studies have demonstrated that geopolymer systems can simultaneously achieve high strength, reduced cost, and lower carbon emissions [Yue Li et al., 2023; Yimiao Huang et al., 2023]. Durability performance is a critical factor in assessing the long-term viability of sustainable concrete. Studies evaluating fly ash utilization through Life Cycle Assessment (LCA) confirm that reusing coal fly ash in construction significantly reduces environmental impacts compared to landfilling or traditional material extraction [Sarah Curpen et al., 2023]. Similarly, environmental evaluations of alkali-activated materials indicate that while alkaline activators contribute to environmental load, optimized mix design and renewable energy integration can considerably lower overall impacts [Sarah Fernando et al., 2022]. Therefore, a comprehensive environmental and economic assessment is necessary to validate the sustainability of geopolymer systems.

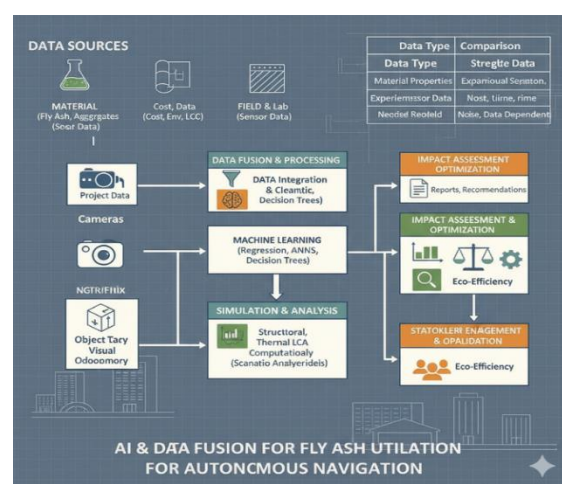


Figure 1.1: Introduction Diagram

In parallel with material innovation, Artificial Intelligence (AI) and machine learning techniques are transforming construction material research. AI-based predictive models

such as Artificial Neural Networks (ANN), Random Forest (RF), Support Vector Machines (SVM), and Extreme Gradient Boosting (XGBoost) have shown high accuracy in predicting compressive strength and optimizing mix proportions of fly ash-based concrete [Geetanjali Khambra et al., 2023; Yiming Peng et al., 2022]. Advanced hybrid optimization frameworks integrating AI with genetic algorithms and particle swarm optimization have demonstrated significant reductions in global warming potential (up to 60%) and production costs (up to 40%) while maintaining structural performance [Vahid Shobeiri et al., 2023; Peyman Zandifaez et al., 2023]. These advancements highlight the importance of integrating AI-driven analytical approaches with experimental investigations to enhance sustainability and performance simultaneously. Despite substantial progress, limited studies comprehensively integrate experimental durability assessment, environmental life cycle evaluation, economic feasibility, and AI-based optimization for M-30 grade geopolymer concrete under practical conditions. Therefore, this research focuses on an AI-based experimental and analytical assessment of fly ash utilization in building projects, comparing Geopolymer Concrete (GPC) with Conventional Concrete (CC) in terms of mechanical performance, durability behavior, carbon emissions, and cost-effectiveness. The outcomes of this study aim to contribute toward sustainable construction practices by proposing geopolymer concrete as a viable, environmentally responsible, and economically feasible alternative to OPC-based concrete.

**Background of Sustainable Construction Materials** The rapid expansion of infrastructure and urbanization has significantly increased the demand for construction materials, particularly concrete. Conventional construction practices rely heavily on non-renewable resources and energy-intensive production processes, contributing to environmental degradation. Sustainable construction materials aim to reduce environmental impacts while maintaining structural integrity, durability, and economic feasibility. Recent studies highlight that waste-derived materials such as fly ash, slag, biomass ash, and recycled aggregates can effectively replace traditional cementitious components, promoting circular economy principles in the construction sector [Lin Chen et al., 2024; Darmansyah et al., 2023]. The integration of supplementary cementitious materials (SCMs) has demonstrated improvements in durability performance and resource efficiency, positioning

sustainable concrete technologies as viable alternatives for modern infrastructure development [Ali Akbar Firooz et al., 2024].

**Environmental Impact of Ordinary Portland Cement (OPC)** Ordinary Portland Cement (OPC) production is a major contributor to global carbon dioxide (CO<sub>2</sub>) emissions due to clinker manufacturing and fossil fuel combustion. The cement industry accounts for a significant portion of global greenhouse gas emissions, accelerating climate change and environmental pollution. Research indicates that reducing clinker content and incorporating industrial by-products can substantially decrease global warming potential (GWP) and embodied energy [Wei Liang et al., 2023]. Life Cycle Assessment (LCA) studies further reveal that cement-based materials exhibit higher environmental burdens compared to alternative binders, particularly in terms of CO<sub>2</sub> emissions and energy consumption [Sarah Curpen et al., 2023]. Therefore, transitioning toward low-carbon binders is essential for achieving sustainable development goals in the construction industry.

**Fly Ash and GGBS as Industrial By-Products** Fly ash (FA) and Ground Granulated Blast Furnace Slag (GGBS) are industrial by-products generated from coal combustion and steel manufacturing processes, respectively. Traditionally disposed of in landfills, these materials pose environmental and health risks due to potential heavy metal leaching [Chaoqiang Wang et al., 2022; Yi Chen et al., 2024]. However, their rich aluminosilicate composition makes them suitable for use as supplementary cementitious materials in concrete production. Experimental investigations demonstrate that appropriate proportions of fly ash enhance compressive strength, reduce permeability, and improve long-term durability [Neha Sharma et al., 2022]. Similarly, high-volume fly ash and slag incorporation have been shown to reduce CO<sub>2</sub> emissions by up to 60% while maintaining structural performance [G.V.P. Bhagath Singh et al., 2024]. Effective utilization of these by-products not only mitigates environmental hazards but also contributes to resource conservation and cost reduction.

**Concept and Fundamentals of Geopolymer Concrete (GPC)** Geopolymer Concrete (GPC) is an innovative binder system formed through the alkaline activation of aluminosilicate materials such as fly ash and GGBS. Unlike OPC hydration, geopolymerization involves a polymeric reaction between silica and alumina in the presence of alkaline activators (e.g., NaOH and Na<sub>2</sub>SiO<sub>3</sub>),

forming a three-dimensional network structure. This process significantly reduces CO<sub>2</sub> emissions compared to traditional cement production. Studies have shown that optimized geopolymers achieve high compressive strength, improved chloride resistance, and enhanced microstructural densification [Muhammad Hassan Ashfaq et al., 2024; Vinay Mohan Agrawal et al., 2023]. Additionally, multi-objective optimization frameworks confirm that geopolymer systems can simultaneously improve strength, reduce carbon footprint, and lower production costs [Yimiao Huang et al., 2023; Yue Li et al., 2023]. These advantages position GPC as a promising sustainable alternative for structural applications.

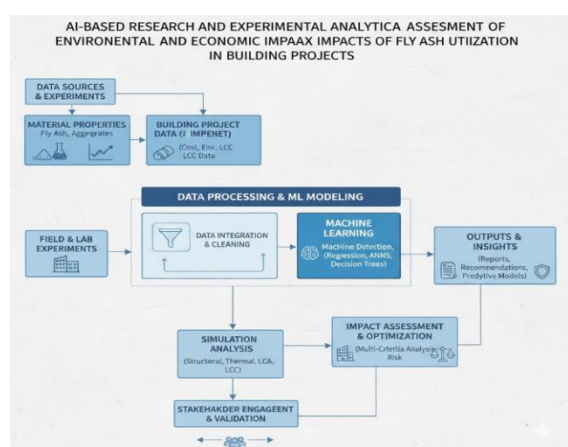


Figure 1.2: Ai-Based Research and Experimental Analytical Assessment

**Comparison Between Conventional Concrete (CC) and GPC** Conventional Concrete (CC) relies on OPC as the primary binder, whereas Geopolymer Concrete (GPC) utilizes industrial waste materials activated by alkaline solutions. Comparative studies indicate that GPC exhibits comparable or superior mechanical properties, improved durability performance, and reduced environmental impact compared to CC [Ayaz Ahmad et al., 2022; Suraj Kumar Parhi et al., 2024]. Life cycle analyses reveal that fly ash-based geopolymer concrete significantly lowers global warming potential and embodied energy compared to traditional cement concrete [Christian Orozco et al., 2024]. However, challenges such as activator cost, curing conditions, and mix optimization remain areas requiring further investigation. Therefore, systematic experimental and analytical assessments are necessary to validate GPC performance for large-scale construction.

### Need for AI-Based Analytical Assessment in Construction

The complexity of concrete mix design, durability

prediction, and environmental performance evaluation necessitates advanced analytical tools beyond traditional empirical methods. Artificial Intelligence (AI) and machine learning (ML) techniques have demonstrated high accuracy in predicting compressive strength and optimizing geopolymer concrete mixtures [Yiming Peng et al., 2022; Geetanjali Khambra et al., 2023]. Hybrid AI-optimization models integrating genetic algorithms and ensemble learning have achieved significant reductions in carbon emissions and production costs while maintaining target strength [Vahid Shobeiri et al., 2023; Peyman Zandifaez et al., 2023]. Furthermore, intelligent models such as Gaussian Process Regression and Support Vector Regression have effectively predicted CO<sub>2</sub> footprints in fly ash geopolymer systems [Y.S. Wudil et al., 2024].

### Aim

To experimentally investigate and analytically evaluate the environmental, economic, and durability performance of geopolymer concrete (GPC) using fly ash and GGBS as sustainable binder materials for M-30 grade construction.

### Objectives

- To design and develop geopolymer concrete (GPC) for M-30 grade using fly ash and ground granulated blast furnace slag (GGBS) as binder materials activated by alkaline solutions (NaOH & Na<sub>2</sub>SiO<sub>3</sub>).
- To assess the durability performance of GPC and CC by conducting:
  - Water Absorption Test to determine porosity and permeability.
  - Acid and Sulfate Resistance Tests to examine durability in aggressive environments.
  - Thermal Resistance Test to assess heat resistance compared to conventional concrete.
- To perform a Life Cycle Assessment (LCA) of both GPC and CC to quantify carbon emissions and environmental impact, focusing on:
  - Reduction in CO<sub>2</sub> emissions due to cement replacement.
  - Comparison of energy consumption in material production and concrete manufacturing.
- To compare the sustainability and cost-effectiveness of GPC and CC in construction applications by evaluating material availability, production feasibility, and long-term durability.
- To propose GPC as a viable alternative to CC for environmentally sustainable construction without compromising on

strength and durability.

### Literature Review

The increasing environmental concerns associated with cement production have accelerated research into sustainable alternatives such as fly ash-based concrete and geopolymers systems. Recent studies emphasize the integration of industrial by-products and artificial intelligence to enhance mechanical performance and sustainability. For instance, fly ash incorporation in 3D printed concrete has demonstrated improved strength and durability when optimized using explainable machine learning models, achieving high predictive accuracy ( $R^2 > 0.997$ ) [Imtiaz Iqbal, 2026]. Similarly, coal bottom ash replacement has been experimentally validated for strength enhancement at later curing ages, with hybrid machine learning models effectively predicting compressive strength [Muhammad Waqas Ashraf, 2025].

Valorization of fly ash has also been explored through closed-loop frameworks integrating metal extraction and geopolymer synthesis, promoting circular economy principles and zero-waste strategies [Siqi Jiang, 2025]. Low-carbon cement production using incineration ash has achieved up to 53.6% reduction in CO<sub>2</sub> emissions compared to traditional cement, demonstrating environmental superiority while maintaining adequate compressive strength [Jie Chen, 2025]. Optimization of fly ash concrete using machine learning and genetic algorithms has further improved mix design efficiency by balancing strength, slump, and carbon emissions [Mingyue Hao, 2025].

Environmental assessments highlight that high-volume fly ash and GGBS replacements significantly reduce greenhouse gas emissions. Studies show reductions of 54–65% in global warming potential when cement is partially replaced by fly ash or slag [Christian Orozco, 2024; G.V.P. Bhagath Singh, 2024]. Life Cycle Assessment (LCA) frameworks confirm that transportation distance and activator dosage significantly influence environmental performance [Sarah Curpen, 2023; Chenchen Luan, 2024]. However, activator production in alkali-activated systems remains a major contributor to embodied emissions [Sarah Fernando, 2022].

Machine learning has emerged as a powerful tool in predicting compressive strength and optimizing sustainable concrete mixes. Advanced models such as XGBoost, Random Forest, Gaussian Process Regression, and Support Vector Regression have demonstrated strong predictive performance with  $R^2$  values exceeding 0.95 [Wei

Liang, 2023; Y.S. Wudil, 2024]. Hybrid AI-optimization techniques integrating Particle Swarm Optimization (PSO) and Genetic Algorithms have enabled multi-objective optimization considering strength, cost, and carbon emissions [Yue Li, 2023; Yimiao Huang, 2023]. Explainable AI approaches using SHAP analysis have further improved transparency in geopolymer mix optimization [Bh Revathi, 2024]. Durability and microstructural performance of geopolymer systems have been extensively investigated. The incorporation of metakaolin with fly ash enhances compressive and flexural strength due to improved geopolymerization and pore refinement [Muhammad Hassan Ashfaq, 2024]. Ternary systems using ultra-fine slag and fly ash significantly improve chloride resistance, sorptivity, and permeability [Vinay Mohan Agrawal, 2023]. Optimization studies confirm that curing temperature, NaOH molarity, and Na<sub>2</sub>SiO<sub>3</sub>/NaOH ratio critically influence mechanical performance [Suraj Kumar Parhi, 2024; Kozo Onoue, 2022].

Environmental toxicity and leaching behavior of fly ash remain critical concerns. Studies have identified heavy metals such as Cd, Hg, Cr, and As in fly ash, highlighting potential ecological risks if improperly managed [Chao-qiang Wang, 2022; Yi Chen, 2024]. Soil contamination studies in India reveal increased elemental leaching under acidic conditions, emphasizing the need for regulated utilization strategies [Chen Luo, 2024]. Nevertheless, controlled alkaline activation has been shown to significantly reduce heavy metal leaching by densifying geopolymer matrices [Xuankun Wei, 2023].

Recent reviews underline the importance of sustainable material conversion and circular economy approaches in construction. Waste-derived construction materials exhibit promising engineering performance but require further research on long-term environmental and economic impacts [Lin Chen, 2024; Darmansyah, 2023]. AI-assisted optimization of green concrete incorporating recycled aggregates has achieved up to 23% cost reduction and 19% global warming reduction while maintaining structural integrity [Peyman Zandifaez, 2023; Vahid Shobeiri, 2023].

### Proposed work

The proposed research aims to conduct a comprehensive experimental and AI-based analytical assessment of fly ash utilization in building projects through the development and evaluation of M-30 grade Geopolymer Concrete (GPC). The study integrates laboratory experimentation, environmental impact assessment, economic evaluation, and machine

learning-based predictive modeling to establish GPC as a sustainable alternative to Conventional Concrete (CC). Initially, geopolymer concrete mixes will be designed using fly ash and Ground Granulated Blast Furnace Slag (GGBS) as primary binder materials. The alkaline activation system will consist of Sodium Hydroxide (NaOH) and Sodium Silicate ( $\text{Na}_2\text{SiO}_3$ ) solutions with optimized molarity and solution ratios. A control mix of M-30 grade Conventional Concrete (CC) using Ordinary Portland Cement (OPC) will be prepared for comparative evaluation. Standard mix design procedures will be followed to ensure consistency in aggregate grading, water-to-binder ratio, and workability. Experimental investigations will include mechanical property evaluation such as compressive strength (cube specimens), split tensile strength (cylinder specimens), and flexural strength (beam specimens) at different curing ages (7, 14, and 28 days). Durability performance will be assessed through water absorption tests to evaluate porosity and permeability, acid resistance and sulfate resistance tests to analyze degradation under aggressive environments, and thermal resistance tests to examine behavior under elevated temperatures. Microstructural characterization may also be conducted to analyze geopolymerization and matrix densification.

To evaluate environmental sustainability, a detailed Life Cycle Assessment (LCA) will be performed for both GPC and CC. The LCA will include goal and scope definition, inventory analysis (material extraction, transportation, manufacturing energy), impact assessment (Global Warming Potential, embodied energy,  $\text{CO}_2$  emissions), and interpretation of results. The study will quantify carbon emission reduction achieved through partial or complete replacement of OPC with fly ash and GGBS. An economic feasibility analysis will also be conducted, comparing material cost, production cost, transportation cost, and long-term maintenance expenses between GPC and CC. The cost-benefit ratio will be analyzed considering durability improvements and reduced environmental penalties.

## Research Methodology

**Research Framework** The research adopts a comparative and analytical framework to evaluate the performance of Geopolymer Concrete (GPC) against Conventional Concrete (CC). The methodology integrates experimental investigation, environmental impact assessment through Life Cycle Assessment (LCA), economic feasibility analysis, and Artificial Intelligence

(AI)-based predictive modeling. This multidisciplinary approach ensures a comprehensive evaluation of mechanical strength, durability characteristics, carbon emissions, and cost-effectiveness to determine the sustainability potential of fly ash-based geopolymer concrete in building applications.

**Materials Selection and Characterization** The primary materials selected for the study include Fly Ash (FA) and Ground Granulated Blast Furnace Slag (GGBS) as binder materials for geopolymer concrete, along with Sodium Hydroxide (NaOH) and Sodium Silicate ( $\text{Na}_2\text{SiO}_3$ ) as alkaline activators. Ordinary Portland Cement (OPC) is used for preparing conventional concrete mixes for comparison. Fine and coarse aggregates conforming to IS standards are used in both mixes. All materials are characterized by determining their specific gravity, fineness, particle size distribution, bulk density, and chemical composition, particularly silica ( $\text{SiO}_2$ ), alumina ( $\text{Al}_2\text{O}_3$ ), and calcium oxide (CaO) content. These properties are essential to understand the geopolymerization process and strength development behavior.

**Mix Design Procedure** The mix design for M-30 grade Conventional Concrete (CC) is carried out as per IS 10262 guidelines, determining appropriate water-cement ratio, aggregate proportioning, and workability. For Geopolymer Concrete (GPC), fly ash and GGBS are used as cementitious binders activated using an alkaline solution. Sodium Hydroxide solution of selected molarity is prepared by dissolving NaOH pellets in distilled water, and it is mixed with Sodium Silicate solution in an optimized ratio. The alkaline liquid-to-binder ratio is determined through trial mixes to achieve target strength and adequate workability. Several trial batches are prepared to finalize the optimum mix proportion for M-30 grade GPC.

**Specimen Preparation and Curing** Concrete specimens are cast in standard molds including cubes (150 mm × 150 mm × 150 mm) for compressive strength testing, cylinders (150 mm × 300 mm) for split tensile strength testing, and beams (100 mm × 100 mm × 500 mm) for flexural strength testing. Proper compaction is ensured using vibration techniques to eliminate air voids and achieve uniform density. Conventional concrete specimens are cured under water curing conditions, while geopolymer concrete specimens are cured under ambient or controlled temperature conditions depending on mix requirements. Testing is conducted at different curing ages such as 7, 14,

and 28 days to evaluate strength development.

**Mechanical Testing** Mechanical properties of both GPC and CC are evaluated through standardized testing procedures. Compressive strength tests are performed on cube specimens using a compression testing machine. Split tensile strength tests are conducted on cylindrical specimens to evaluate tensile resistance. Flexural strength tests are carried out on beam specimens to assess bending performance. The results are analyzed to compare strength gain, load-bearing capacity, and overall structural performance between geopolymer and conventional concrete.

**Durability Assessment** Durability performance is assessed through multiple tests to simulate aggressive environmental conditions. Water absorption tests are conducted to determine porosity and permeability characteristics of the concrete matrix. Acid resistance tests involve immersing specimens in acidic solutions and measuring weight and strength loss over time. Sulfate resistance tests evaluate the effect of sulfate exposure on structural integrity. Thermal resistance tests are performed by exposing specimens to elevated temperatures to analyze performance under heat stress. These tests help determine long-term serviceability and environmental resistance of GPC compared to CC.

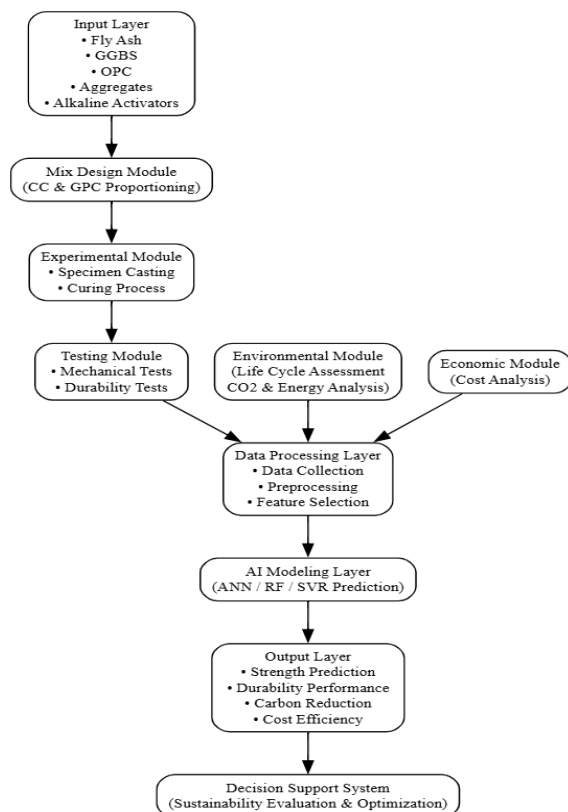


Figure 1.2: Methodology Flow chart

**Life Cycle Assessment (LCA)** A cradle-to-gate Life Cycle Assessment approach is adopted to evaluate environmental impacts associated with both GPC and CC production. The LCA includes inventory analysis covering raw material extraction, transportation, processing, and manufacturing energy consumption. Environmental impact indicators such as Global Warming Potential (GWP), embodied energy, and CO<sub>2</sub> emissions are calculated. The reduction in carbon emissions achieved through partial or complete replacement of OPC with fly ash and GGBS is quantified to assess sustainability benefits.

**Economic Feasibility Analysis** An economic analysis is performed to compare the cost-effectiveness of GPC and CC. This includes material cost evaluation, cost of alkaline activators, transportation expenses, and production costs. Additionally, long-term maintenance costs are considered based on durability performance. A cost-performance index is developed to determine the economic viability of geopolymer concrete for practical construction applications.

**AI-Based Predictive Modeling** Artificial Intelligence techniques are implemented to enhance analytical assessment. Experimental data obtained from mechanical and durability testing are compiled into a dataset. Data preprocessing techniques such as normalization, feature selection, and outlier removal are applied.

**Result Integration and Validation** The final stage involves integrating experimental findings, LCA results, economic analysis, and AI model predictions. Comparative performance evaluation is conducted to validate whether geopolymer concrete can serve as a sustainable and durable alternative to conventional concrete. The overall sustainability index is developed considering strength, durability, cost, and carbon emission reduction. Conclusions are drawn based on technical feasibility, environmental benefits, and economic practicality.

## Material used

### 1. Fly Ash



Figure 1.3: Fly Ash

<https://share.google/rl5buGUDmpHujkMtl>

An industrial by-product obtained from thermal power plants. It has a smooth texture and is commonly used as a supplementary cementitious material in geopolymer and conventional concrete. Fly ash enhances workability, durability, and reduces the carbon footprint of concrete.

### 2. Ground Granulated Blast Furnace Slag (GGBS):



Figure 1.4: Ground Granulated Blast Furnace Slag (GGBS)

<https://share.google/Dyo34ce508Tsm2YRX>

The image shows Ground Granulated Blast Furnace Slag (GGBS), a fine off-white powder obtained as a by-product from the iron manufacturing process. It is rich in calcium and silica, making it an effective supplementary cementitious material in concrete. GGBS improves strength development, durability, and resistance to chemical attack while reducing carbon emissions.

### 3. Ordinary Portland Cement (OPC)



Figure 1.5: Ordinary Portland Cement (OPC)  
<https://share.google/3ktEx84VZdlxgr1QJ>

Figure 1.5 shows Ordinary Portland Cement (OPC) as a fine gray powder stored in a cloth bag. OPC is the most widely used cement, made by grinding clinker with gypsum for hydration and hardening in construction. It offers high compressive strength and durability for concrete, mortar, and general building projects

### 4. Fine Aggregate



Figure 1.6: Fine Aggregate  
<https://share.google/mnflORjMbESPG4bpS>

Figure 1.6 shows fine aggregate as a pile of natural sand particles smaller than 4.75 mm, essential for concrete mixes.

It fills voids between coarse aggregates, improves workability, and enhances concrete strength and cohesion.

Typical properties include specific gravity 2.5-2.9 and fineness modulus 2.3-3.1 for optimal performance.

## 5.Coarse Aggregate



Figure 1.7: Coarse Aggregate  
<https://share.google/TlfrMMH9HICO5t5y0>

Figure 1.7 shows coarse aggregate as a pile of crushed stones and gravel larger than 4.75 mm, typically angular or rounded. It forms 60-75% of concrete volume, providing bulk strength, durability, and load-bearing capacity. Key properties: specific gravity 2.6-2.9, size 5-40 mm, low absorption (<2%), and resistance to crushing.

## 6.Sodium Hydroxide (NaOH)



Figure 1.8: Sodium Hydroxide (NaOH):  
[https://en.wikipedia.org/wiki/Sodium\\_hydroxide](https://en.wikipedia.org/wiki/Sodium_hydroxide)

Figure 1.8 shows Sodium Hydroxide (NaOH) pellets, white and translucent solid flakes used as an alkali activator. In geopolymer concrete with fly ash, NaOH dissolves aluminosilicates to enable polymerization and strength development. Typically, 8-14 M concentration, it generates heat during mixing and requires careful handling due to corrosiveness.

## 7.Sodium Silicate ( $\text{Na}_2\text{SiO}_3$ )



Figure 1.9: Sodium Silicate ( $\text{Na}_2\text{SiO}_3$ )  
<https://share.google/4A2i2o15sph71guf0>

Figure 1.9 shows Sodium Silicate ( $\text{Na}_2\text{SiO}_3$ ) as white powder flakes (a) and its clear liquid solution (b) in a beaker. As an alkali activator in fly ash geopolymer concrete, it provides soluble silica for geopolymerization, enhancing matrix formation and compressive strength. Typically used at  $\text{Na}_2\text{SiO}_3/\text{NaOH}$  ratios of 1.5-2.5, it contributes to early strength gain and durability in sustainable construction.

## 8. Water



Figure 1.10: Water  
<https://share.google/AxzgMUYOMF8iHQkUg>

Figure 1.10 depicts water as clear, splashing droplets essential for hydration in cementitious materials like OPC and geopolymer concrete. In fly ash geopolymer mixes, water facilitates dissolution of NaOH and  $\text{Na}_2\text{SiO}_3$  activators, enabling aluminosilicate polymerization for strength development. Potable water with pH 6.5-8.5 and <2000 ppm solids is ideal to avoid impurities affecting setting time and durability.

## Results And Discussion

The experimental results indicate that the Fly Ash and GGBS-based Geopolymer Concrete (GPC) successfully achieved the target strength requirements for M-30 grade concrete. The compressive strength results showed that GPC exhibited comparable or slightly higher strength than Conventional Concrete (CC) at 28 days. Early-age strength development was satisfactory under ambient curing conditions, indicating effective geopolymerization and binder formation. Split tensile and flexural strength results followed a similar trend, confirming adequate bonding between aggregates and geopolymer matrix. Durability test results demonstrated that GPC exhibited lower water absorption values compared to CC, indicating reduced porosity and a denser microstructure. Acid resistance and sulfate resistance tests revealed lower percentage weight loss and strength reduction in GPC specimens, suggesting improved resistance to aggressive environmental conditions. Thermal resistance evaluation showed that GPC retained higher residual strength after exposure to elevated temperatures, highlighting its better performance under heat stress.

The Life Cycle Assessment (LCA) results confirmed a significant reduction in CO<sub>2</sub> emissions and embodied energy due to the elimination of Ordinary Portland Cement (OPC). The environmental impact analysis clearly showed that cement replacement with fly ash and GGBS substantially lowers the carbon footprint of concrete production. Economic analysis indicated that while the cost of alkaline activators increases initial material cost, improved durability and potential reduction in maintenance costs enhance long-term economic feasibility. AI-based predictive models demonstrated high accuracy in estimating compressive strength and environmental impact parameters, supporting efficient mix optimization.

## Conclusion And Future Scope

This study evaluates the mechanical, durability, environmental, and economic performance of Fly Ash-based Geopolymer Concrete (GPC) in comparison with Conventional Concrete (CC) for M-30 grade applications. The experimental investigation demonstrates that GPC can achieve comparable or superior compressive, tensile, and flexural strength while exhibiting improved resistance to water absorption, acid attack, sulfate exposure, and elevated temperatures. The Life Cycle Assessment (LCA) confirms a significant reduction in CO<sub>2</sub> emissions and embodied energy due to partial or complete

replacement of Ordinary Portland Cement (OPC) with fly ash and GGBS. Economic analysis indicates that although alkaline activators may increase initial material cost, long-term durability and reduced maintenance requirements enhance overall cost-effectiveness. The integration of Artificial Intelligence (AI) further strengthens predictive accuracy and mix optimization. Overall, the research establishes Geopolymer Concrete as a technically viable, environmentally sustainable, and economically feasible alternative for modern construction practices.

## Summary of Key Findings

The study confirmed that Fly Ash and GGBS-based Geopolymer Concrete (GPC) achieved the required M-30 grade strength with comparable or improved compressive, tensile, and flexural performance compared to Conventional Concrete (CC). Durability tests showed lower water absorption and better resistance to acid, sulfate, and thermal exposure, indicating enhanced long-term performance. Life Cycle Assessment (LCA) revealed a significant reduction in CO<sub>2</sub> emissions and embodied energy due to cement replacement. Although initial costs may be slightly higher, improved durability makes GPC economically viable. Overall, GPC proved to be a sustainable and efficient alternative for modern construction.

## Limitations

This study has certain limitations that should be considered while interpreting the results. The experimental investigation was conducted under controlled laboratory conditions, which may not fully replicate real-world environmental exposure. The study focused on M-30 grade concrete; therefore, the findings may not directly represent the performance of higher or lower strength grades. Long-term durability performance beyond the testing period was not extensively evaluated. Variations in fly ash and GGBS chemical composition from different sources may influence geopolymerization behavior and strength development. Additionally, the cost analysis was based on current market prices, which may vary regionally and over time. The AI-based models were developed using limited experimental datasets, and larger datasets could improve prediction accuracy.

## Ethical and Societal Impact

The use of fly ash-based Geopolymer Concrete (GPC) promotes environmental sustainability by reducing dependence on Ordinary Portland Cement (OPC), thereby lowering CO<sub>2</sub> emissions

and minimizing environmental pollution. The utilization of industrial by-products such as fly ash and GGBS supports waste management and circular economy principles. From a societal perspective, GPC can enhance infrastructure durability, reduce long-term maintenance costs, and contribute to safer and more sustainable construction practices. Overall, the study supports environmentally responsible innovation and sustainable development in the construction industry.

### Future Research Opportunities

The present study establishes the feasibility of fly ash-based Geopolymer Concrete (GPC) as a sustainable alternative to Conventional Concrete (CC); however, several avenues remain open for future research. Long-term durability studies under real field exposure conditions, including marine, coastal, and industrial environments, can provide deeper insights into performance over extended service life. Further investigation into high-performance and ultra-high-performance geopolymer concrete mixes, incorporating nano-materials such as nano-silica, graphene oxide, or fibers, may enhance mechanical and durability properties. Advanced microstructural analysis using SEM, XRD, and FTIR techniques can be conducted to better understand geopolymerization mechanisms and interfacial bonding behavior. Future studies may also explore large-scale structural applications of geopolymer concrete in beams, slabs, columns, and precast elements to validate practical feasibility. The integration of carbon capture materials or alternative industrial by-products such as rice husk ash, silica fume, or red mud could further improve environmental performance. From an analytical perspective, more sophisticated Artificial Intelligence models, including deep learning and hybrid optimization algorithms, can be developed to predict long-term durability, structural behavior, and life-cycle costs with higher accuracy. Additionally, comprehensive cradle-to-grave Life Cycle Assessments and policy-level sustainability frameworks may be explored to support standardization and large-scale adoption of geopolymer technology in the construction industry.

### Compliance with Ethical Standards

This research study titled "AI-Based Research and Experimental Analytical Assessment of Environmental and Economic Impacts of Fly Ash Utilization in Building Projects" has been conducted in full compliance with established academic and research ethical standards. The study is entirely experimental and analytical in

nature and does not involve human participants, animal subjects, or clinical investigations; therefore, formal ethical approval was not required. All experimental procedures were carried out using standard laboratory practices and in accordance with relevant Indian Standards (IS codes) to ensure accuracy, reliability, and reproducibility of results. The data generated in this research are based on controlled laboratory experiments and verified analytical methods, and no form of data fabrication, manipulation, or misrepresentation has been undertaken. Proper citation and referencing practices have been strictly followed to acknowledge prior research contributions and avoid plagiarism. The authors declare that there is no conflict of interest associated with this study, and the research has been conducted solely for academic and scientific purposes, maintaining transparency, integrity, and environmental responsibility throughout the investigation.

### References

- Imtiaz Iqbal et al., "Strength characterisation of fly ash blended 3D printed concrete enhanced with explainable machine learning" *Case Studies in Construction Materials*, Elsevier, Volume 24, 2026, e05682. <https://doi.org/10.1016/j.cscm.2025.e05682>
- Muhammad Waqas Ashraf et al., "Experimental and explainable machine learning based investigation of the coal bottom ash replacement in sustainable concrete production" *Journal of Building Engineering*, Elsevier, Volume 104, 2025. Page No. 112367. <https://doi.org/10.1016/j.jobbe.2025.112367>
- Siqi Jiang et al., "Closed-loop valorization of fly ash: Integrating selective metal extraction and multi-solid-waste geopolymer synthesis for circular economy" *Separation and Purification Technology*, Elsevier, Volume 374, 2025. Page No. 133664. <https://doi.org/10.1016/j.seppur.2025.133664>
- Jie Chen et al., "Development of low-carbon cement utilizing waste incineration ash: Mechanical properties, hydration behavior, and environmental impact" *Construction and Building Materials*, Elsevier, Volume 481, 2025. Page No. 141584. <https://doi.org/10.1016/j.conbuildmat.2025.141584>
- Mingyue Hao et al., "Optimization design method of C30/C40 fly ash concrete based on machine learning and elite retention genetic algorithm" *Advances in Engineering Software*, Elsevier,

Volume 210, 2025. Page No. 104019.  
<https://doi.org/10.1016/j.advengsoft.2025.104019>

Jelena Horvatinec et al., "Recycling fly ash from coal or biomass combustion for nutrient recovery and enhanced food production in acidic agroecosystems: A multi-level meta-analysis" *Renewable and Sustainable Energy Reviews*, Volume 221, 2025, 115925. <https://doi.org/10.1016/j.rser.2025.115925>

Mohammed Rihan Maaze et al., "A holistic approach and frame work to optimized fly ash cement brick production integrating technical, life cycle cost and environmental life cycle assessment" *Cleaner Materials*, Elsevier, Volume 17, 2025. Page No.100329. <https://doi.org/10.1016/j.clema.2025.100329>

Siva Shanmukha Anjaneya Babu Padavala et al., "Experimental and machine learning based analysis of pervious concrete enhanced with fly ash and silica fume" *Next Materials*, Elsevier, Volume 9, 2025. Page No.101018. <https://doi.org/10.1016/j.nxmate.2025.101018>

Y.S. Wudil et al., "Intelligent optimization for modeling carbon dioxide footprint in fly ash geopolymer concrete: A novel approach for minimizing CO<sub>2</sub> emissions" *Journal of Environmental Chemical Engineering*, Elsevier, Volume 12, Issue 1, 2024. Page No.111835. <https://doi.org/10.1016/j.jece.2023.111835>

Christian Orozco et al., "Comparison of environmental impacts of fly ash and slag as cement replacement materials for mass concrete and the impact of transportation" *Sustainable Materials and Technologies*, Elsevier, Volume 39, 2024. Page No.e00796. <https://doi.org/10.1016/j.susmat.2023.e00796>

Mengke Li et al., "Preparation and characterization of low-activity coal bottom ash-based cementitious materials via orthogonal experiment" *Journal of Building Engineering*, Elsevier, Volume 96, 2024. Page No.110495. <https://doi.org/10.1016/j.job.2024.110495>

Supriya Janga et al., "Assessment of thermal and mechanical properties of fly ash based geopolymer blocks with a sustainability perspective using multi-criteria decision-making approach" *Journal of Building Engineering*, Elsevier, Volume 88, 2024. Page No.109261. <https://doi.org/10.1016/j.job.2024.109261>

G.V.P. Bhagath Singh et al., "Environmental impact of concrete containing high volume fly ash and ground granulated blast furnace slag" *Journal of Cleaner Production*, Elsevier, Volume 448, 2024. Page No.141729. <https://doi.org/10.1016/j.jclepro.2024.141729>

Tariq Ali et al., "A systematic literature review of AI-based prediction methods for self-compacting, geopolymer, and other eco-friendly concrete types: Advancing sustainable concrete" *Construction and Building Materials*, Elsevier, Volume 440, 2024. Page No. 137370. <https://doi.org/10.1016/j.conbuildmat.2024.137370>

Suraj Kumar Parhi et al., "AI-driven critical parameter optimization of sustainable self-compacting geopolymer concrete" *Journal of Building Engineering*, Elsevier, Volume 86, 2024. Page No.108923. <https://doi.org/10.1016/j.job.2024.108923>

Chenchen Luan et al., "CO<sub>2</sub> avoidance cost of fly ash geopolymer concrete" *Construction and Building Materials*, Elsevier, Volume 416, 2024. Page No.135193. <https://doi.org/10.1016/j.conbuildmat.2024.135193>

Yi Chen et al., "A comprehensive review of toxicity of coal fly ash and its leachate in the ecosystem" *Ecotoxicology and Environmental Safety*, Elsevier, Volume 269, 2024, 115905. <https://doi.org/10.1016/j.ecoenv.2023.115905>

Bh Revathi et al., "Harnessing explainable Artificial Intelligence (XAI) for enhanced geopolymer concrete mix optimization" *Results in Engineering*, Elsevier, Volume 24, 2024. Page No.103036. <https://doi.org/10.1016/j.rineng.2024.103036>

Jelena Horvatinec et al., "Fly ash application impacts master physicochemical pedovariates: A multilevel meta-analysis" *Journal of Environmental Management*, Elsevier, Volume 368, 2024, 122066. <https://doi.org/10.1016/j.jenvman.2024.122066>

Chen Luo et al., "Soil contamination caused by fly ash from coal-fired thermal power plants in India: Spatiotemporal distribution and elemental leaching potential" *Applied Geochemistry*, Volume 170, 2024,

106080.<https://doi.org/10.1016/j.apgeochem.2024.106080>

Madushan Rathnayaka et al., "Machine learning approaches to predict compressive strength of fly ash-based geopolymer concrete: A comprehensive review" *Construction and Building Materials*, Volume 419, 2024, 135519.<https://doi.org/10.1016/j.conbuildmat.2024.135519>

Mihaela Oleksik et al., "Advanced use of waste rubber and fly ash to ensure an efficient circular economy" *Ain Shams Engineering Journal*, Elsevier, Volume 15, Issue 1, 2024. Page No. 102264.  
<https://doi.org/10.1016/j.asej.2023.102264>

Md. Habibur Rahman Sobuz et al., "Assessing the influence of sugarcane bagasse ash for the production of eco-friendly concrete: Experimental and machine learning approaches" *Case Studies in Construction Materials*, Elsevier, Volume 20, 2024, e02839.<https://doi.org/10.1016/j.cscm.2023.e02839>

Muhammad Hassan Ashfaq et al., "Up-scaling of fly ash-based geopolymer concrete to investigate the binary effect of locally available metakaolin with fly ash" *Heliyon*, Volume 10, Issue 4, 2024. Page No. e26331.  
<https://doi.org/10.1016/j.heliyon.2024.e26331>

Lin Chen et al., "Conversion of waste into sustainable construction materials: A review of recent developments and prospects" *Materials Today Sustainability*, Elsevier, Volume 27, 2024, Page No. 100930.  
<https://doi.org/10.1016/j.mtsust.2024.100930>

Ali Akbar Firooz et al., "Emerging trends in sustainable building materials: Technological innovations, enhanced performance, and future directions" *Results in Engineering*, Elsevier, Volume 24, 2024, 103521.  
<https://doi.org/10.1016/j.rineng.2024.103521>

Geetanjali Khambra et al., "Novel machine learning applications on fly ash-based concrete: An overview" *Material Today Proceeding*, Elsevier, Volume 80, Part 3, 2023, Pages 3411-3417.<https://doi.org/10.1016/j.matpr.2021.07.262>

Wei Liang et al., "Mixed artificial intelligence models for compressive strength prediction and analysis of fly ash concrete" *Advances in Engineering Software*, Elsevier, Volume 185, 2023. Page No. 103532.

<https://doi.org/10.1016/j.advensoft.2023.103532>

Sarah Curpen et al., "Evaluating life cycle environmental impacts of coal fly ash utilization in embankment versus sand and landfilling" *Journal of Cleaner Production*, Elsevier, Volume 385, 2023. Page No. 135402.  
<https://doi.org/10.1016/j.jclepro.2022.135402>

Darmansyah Darmansyah et al., "Advancements of coal fly ash and its prospective implications for sustainable materials in Southeast Asian countries: A review" *Renewable and Sustainable Energy Reviews*, Elsevier, Volume 188, 2023. Page No. 113895.  
<https://doi.org/10.1016/j.rser.2023.113895>

Mengting Wu et al., "Evaluating the metal recovery potential of coal fly ash based on sequential extraction and machine learning" *Environmental Research*, Elsevier, Volume 224, 2023. Page No. 115546.  
<https://doi.org/10.1016/j.envres.2023.115546>

Xuankun Wei et al., "Co-disposal of hazardous waste incineration fly ash and bottom ash through alkaline-activation: Effects of added CaO on solidification of heavy metals" *Journal of Environmental Chemical Engineering*, Elsevier, Volume 11, Issue 5, 2023. Page No. 110924.  
<https://doi.org/10.1016/j.jece.2023.110924>

Yue Li et al., "Optimization design for alkali-activated slag-fly ash geopolymer concrete based on artificial intelligence considering compressive strength, cost, and carbon emission" *Journal of Building Engineering*, Elsevier, Volume 75, 2023. Page No. 106929.  
<https://doi.org/10.1016/j.jobbe.2023.106929>

Vinay Mohan Agrawal et al., "Optimization of ternary concrete made using slag and fly ash in ultra-fine form using desirability function approach" *Material Today Proceeding*, Volume 93, Part 3, 2023, Pages 370-376.  
<https://doi.org/10.1016/j.matpr.2023.07.345>

Yimiao Huang et al., "Multi-objective optimization of fly ash-slag based geopolymer considering strength, cost and CO<sub>2</sub> emission: A new framework based on tree-based ensemble models and NSGA-II" *Journal of Building Engineering*, Elsevier, Volume 68, 2023. Page No. 106070.  
<https://doi.org/10.1016/j.jobbe.2023.106070>

João Peres Ribeiro et al., "Granulated biomass fly ash coupled with fenton process for pulp and paper wastewater treatment" *Environmental*

Pollution, Elsevier, Volume 317, 2023, 120777.<https://doi.org/10.1016/j.envpol.2022.120777>

Peyman Zandifaez et al., "AI-Assisted optimisation of green concrete mixes incorporating recycled concrete aggregates" Construction and Building Materials, Elsevier, Volume 391, 2023, 131851.<https://doi.org/10.1016/j.conbuildmat.2023.131851>

Vahid Shobeiri et al., "Mix design optimization of concrete containing fly ash and slag for global warming potential and cost reduction" Case Studies in Construction Materials, Volume 18, 2023, e01832. <https://doi.org/10.1016/j.cscm.2023.e01832>

Sarah Fernando et al., "Environmental evaluation and economic analysis of fly ash-rice husk ash blended alkali-activated bricks" Environmental Impact Assessment Review, Elsevier, Volume 95, 2022, Page No.106784. <https://doi.org/10.1016/j.eiar.2022.106784>

Mahdi Rafieizonooz et al., "Assessment of environmental and chemical properties of coal ashes including fly ash and bottom ash, and coal ash concrete" Journal of Building Engineering, Elsevier, Volume 49, 2022, Page No.104040. <https://doi.org/10.1016/j.jobe.2022.104040>

Neha Sharma et al., "An Experimental investigation of Sustainable Concrete by incorporating E-waste and Fly Ash" Material Today Proceeding, Elsevier, Volume 62, Part 6, 2022, Pages 4188-4193. <https://doi.org/10.1016/j.matpr.2022.04.704>

Kozo Onoue et al., "Optimization of mix proportions and manufacturing conditions of fly ash-based geopolymer mortar by parameters design with dynamic characteristics" Cement and Concrete Composites, Elsevier, Volume 133, 2022, Page No.104645. <https://doi.org/10.1016/j.cemconcomp.2022.104645>

Yiming Peng et al., "Analyzing the mechanical performance of fly ash-based geopolymer concrete with different machine learning techniques" Construction and Building Materials, Elsevier, Volume 316, 2022, Page No.125785. <https://doi.org/10.1016/j.conbuildmat.2021.125785>

M. Aminul Haque et al., "Evaluating the mechanical strength prediction performances of fly ash-based MPC mortar with artificial

intelligence approaches" Journal of Cleaner Production, Elsevier, Volume 355, 2022, Page No.131815. <https://doi.org/10.1016/j.jclepro.2022.131815>

Chao-qiang Wang et al., "Utilization of fly ash as building material admixture: Basic properties and heavy metal leaching" Case Studies in Construction Materials, Elsevier, Volume 17, 2022, Page No. e01422. <https://doi.org/10.1016/j.cscm.2022.e01422>

Ayaz Ahmad et al., "Compressive strength prediction of fly ash-based geopolymer concrete via advanced machine learning techniques" Case Studies in Construction Materials, Elsevier, Volume 16, 2022, Page No. e00840. <https://doi.org/10.1016/j.cscm.2021.e00840>

Mugahed Amran et al., "Innovative use of fly ash-finely powdered glass cullet as a nanoadditives for a sustainable concrete: Strength and microstructure and cost analysis" Case Studies in Construction Materials, Elsevier, Volume 17, 2022, Page No. e01688. <https://doi.org/10.1016/j.cscm.2022.e01688>

Madiha Ahmad et al., "Utilization of a novel artificial intelligence technique (ANFIS) to predict the compressive strength of fly ash-based geopolymer" Construction and Building Materials, Elsevier, Volume 301, 2021, Page No.124251. <https://doi.org/10.1016/j.conbuildmat.2021.124251>

Tse-Lun Chen et al., "A systematic approach to evaluating environmental-economic benefits of high-gravity technology for flue gas purification and municipal solid waste incineration fly ash utilization" Journal of Environmental Chemical Engineering, Elsevier, Volume 9, Issue 6, 2021, Page No.106438. <https://doi.org/10.1016/j.jece.2021.106438>

Fuzail Hashmi et al., "Optimization of fly ash concrete mix - a solution for sustainable development" Material Today Proceeding, Volume 26, Part 2, 2020, Pages 3250-3256. <https://doi.org/10.1016/j.matpr.2020.02.908>